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HIGH PRECISION TIDAL GRAVITY(U) INSTITUTE OF
OCEANOGRAPHIC SCIENCES BIRKENHEAD (ENGLAND)
T F BAKER ET AL. 20 JUN 85 AFGL-TR-85-0203

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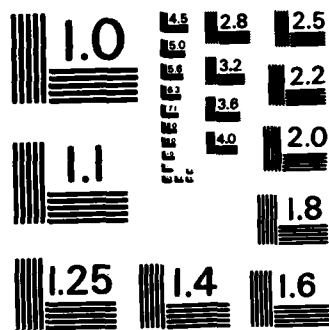
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CONTRACT OR GRANT NO. AFOSR 84-0071

HIGH PRECISION TIDAL GRAVITY

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Final Report
1 March 1984 - 28 February 1985

20 June 1985

Approved for public release; distribution unlimited

Prepared for

AIR FORCE GEOPHYSICS LABORATORY
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
HANSOM AFB, MASSACHUSETTS 01731

and

EUROPEAN OFFICE OF AEROSPACE RESEARCH AND DEVELOPMENT
LONDON, ENGLAND

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. Report Number AFGL-TR-85-0203	2. Govt Accession No. <i>AD-A160676</i>	3. Recipient's Catalog Number
4. Title (and Subtitle) HIGH PRECISION TIDAL GRAVITY	5. Type of Report & Period Covered SCIENTIFIC REPORT 1 March 1984 to 28 February 1985	
	6. Performing Org. Report Number	
7. Author(s) BAKER T.F., EDGE R.J. AND JEFFRIES G.	8. Contract or Grant Number AFOSR 84-0071	
9. Performing Organization Name and Address INSTITUTE OF OCEANOGRAPHIC SCIENCES NATURAL ENVIRONMENT RESEARCH COUNCIL BIDSTON OBSERVATORY, BIRKENHEAD L43 7RA.U.K.	10. Program Element, Project, Task Area & Work Unit Numbers 61102F 2309G1AZ	
11. Controlling Office Name and Address Air Force Geophysics Laboratory/LWG Hanscom AFB, MA01731 Monitor/Andrew R. Lazarewicz	12. Report Date 20 June 1985	
	13. Number of Pages 14	
14. Monitoring Agency Name and Address	15.	
16. & 17. Distribution Statement Approved for public release; distribution unlimited.		
18. Supplementary Notes		
19. Key Words EARTH TIDES; TIDAL GRAVIMETERS; OCEAN TIDE LOADING, Great Britain. ←		
20. Abstract This report discusses recent progress on the programme of 'high precision tidal gravity'. The programme is now primarily concerned with the field measurement of tidal gravity and a description of present experiments and preliminary results is given. The preliminary results show that a measurement accuracy in amplitude for the principal tidal harmonics O1 and M2 of $\pm 0.2\%$ is achievable and that phases may be determined to $\pm 0.1^\circ$. This is approaching an order of magnitude improvement over existing measurements. The conclusion contains a summary of the major achievements of the first 5 years of the I.O.S. tidal gravity programme.		

HIGH PRECISION TIDAL GRAVITY: Final Scientific Report
March 1984 - February 1985

INTRODUCTION

This scientific report contains details of work completed during the year of the I.O.S. 'high precision tidal gravity' programme. This programme has been partly supported by AFOSR. The work was commenced in 1980 with the aim of improving existing tidal gravity measurements by the use of LaCoste and Romberg Earth Tide gravimeters, particularly in regions of large ocean tide loading (i.e. close to ocean tide antiamphidromes). Following the first phase of the programme, which involved substantial instrumental modifications and extensive testing and calibration under ideal laboratory conditions, the programme moved into the "data gathering" phase. It is in this area that the majority of the work described in the report falls. The final phase of the programme is the interpretation of the measurements which will be used to constrain the latest theoretical ocean tide and Earth body tide models.

Full details of the scientific basis for the programme have already been presented in earlier scientific reports ^{1,2,3} and will not be presented again here. It is however relevant to comment that since the onset of the programme the interest in accurate tidal gravity measurements has increased substantially - mainly to assist in the interpretation of data obtained from modern geodetic techniques such as VLBI, laser ranging, satellite altimetry and absolute gravity determinations. The demand for tidal information from the geodynamics area of geophysics has also increased substantially. To some extent the original programme has been modified to meet this demand.

As in previous reports this document describes firstly instrumental developments followed by a description of the experiments undertaken during the period of the grant. Some preliminary results and their implications are discussed together with a brief discussion of expected future developments to the programme. Finally the conclusion summarises not only the achievements of this last year but also the major achievements of the first 5 years of this ongoing tidal gravity measurement programme.



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INSTRUMENTAL DEVELOPMENTS

At the beginning of the year under report, three identical, complete gravimeter systems comprising LaCoste and Romberg E.T.10, E.T.13 and E.T.15 were available for use. Each system comprises of the gravimeter, associated operating and recording systems and monitors to ensure that long continuous, reliable and well monitored data are obtained from instrument deployments. These instruments have all been deployed gathering data; thus the opportunity, and need, for additional instrumental developments has been minimal. However some progress has been made with the digital data loggers and the timing accuracy of the systems.

(a) Digital data logging

The process of replacing the ageing RAPCO loggers by MICRODATA loggers was completed. This has led to greater reliability and greater flexibility in the data recorded and thus improved the initial stages of data processing.

(b) Quartz clocks

Experience in the field deployments showed that the independent, free running, quartz clocks occasionally drifted out of their specification of ± 3 secs per month. This was due to the temperature sensitivity of the frequency standard. Modifications to compensate this temperature sensitivity have been made although, in the longer term replacement is the better alternative. Developments using an acoustic coupler connected to the audio output of a carefully selected quartz chronometer are very promising.

To summarise, major instrumental developments took place during 1980-84. As will be seen in later sections, the investment has been shown to be very worthwhile. Three reliable gravimeter systems are fully operational.

TIDAL GRAVITY EXPERIMENTS

Table 1 shows the experimental deployments made during the period of AFOSR support. It can clearly be seen that in recent years these deployments have increased and that the data gathering phase is well underway. All gravimeter systems have been used. During the coming year further installations in Europe and an installation on the Indian sub-continent are expected. Details of these deployments follows.

In all cases the deployment procedures have followed the detailed description given in ref. 2. Evidence that all deployments have achieved a similar precision is indicated by the preliminary hourly residuals

after removal from the data of long term drift and tides. In all experiments analysed so far the standard deviation of these individual hourly residuals is in the range 0.65 to 0.95 μ gals and is to some extent seasonally and site dependent.

One particularly encouraging feature of all the deployments completed so far is the remarkably stable calibration of the complete electronic system both in amplitude and phase. Internal calibrations carried out at both the beginning and end of a deployment, even after a year of operation, show agreement at the 0.05% level.

ET10: HANSCOM FIELD AFB

Results from this deployment have already been reported ³. The experiment was performed to provide tidal loading corrections accurate to $\pm 1 \mu$ gal which may be applied to absolute gravity measurements made at the site. Observations were a requirement for the site owing to the close proximity of the ocean tides of the N.W. Atlantic Ocean and the problems of models in the Boston Harbour region. The use of existing numerical models would not provide the constraints required. From the tidal harmonics determined from the experimental deployment, corrections may be made for body tide and tidal loading at the required precision for any chosen epoch.

EXPERIMENTS AT I.O.S. BIDSTON

It may be seen from Table 1 that all systems have been deployed at I.O.S. Bidston to ensure system reliability and accuracy. Preliminary results for a single month of simultaneous operation of E.T.13 and E.T.15 were presented in the last scientific report ³. Additional analyses of a further two months of simultaneous data from E.T.13 and E.T.15 and a preliminary analysis of six months of data from E.T.10, accumulated at a later time, have been completed.

At this stage comparatively simple analyses have been completed. In all cases raw data from each experiment have been reduced to hourly values, filtered using a Doodson-Lennon X_0 tidal filter and analysed for tides using the standard analysis procedures of HYCON using 13 tidal wave groups. The results for the principal diurnal constituent, O_1 , and the principal semi-diurnal constituent, M_2 , are given in Table 2. These preliminary analyses may be used directly to show the excellent internal precision

of the measurements. When coupled with the calibrations performed on all instruments at Hannover, F.R.G. the measurements may be regarded as highly accurate. The amplitudes of the waves from all 3 gravimeters agree at the $\pm 0.2\%$ level and the phases to within 0.1° . This degree of precision and accuracy approaches an order of magnitude improvement on existing tidal gravity observations published by the International Centre for Earth Tides (ICET), and confirms that these gravimeter systems are capable of testing both body tide models and ocean tide models much more rigorously. The present situation concerning existing observations and theory is probably best summarised by Figure 1 which has been adapted from Merriam⁴. The figure shows the published ICET M_2 gravimetric factors for stations at distances greater than 300km from the ocean, after correction for ocean loading using the Schwiderski⁵ 1° ocean tide model. The different symbols refer to different types of gravimeter while the continuous curve is the theoretical M_2 gravimetric factor, as a function of latitude, for the Wahr⁶ M_2 body tide model.

EXPERIMENTS AT BRUSSELS AND BAD HOMBERG

Sufficient data have been obtained from both experiments to provide some of the rigorous testing of body tide models and ocean tide models indicated above. These data are still being pre-processed and analysed and it is premature to publish figures here. However there are strong indications that the data will make a significant contribution to present understanding of tidal gravity observations. Appendix 1, an abstract of an informal presentation to European geodynamicists made earlier this year, indicates one area in which this contribution may be made. It must be emphasised that, in parallel with the analysis of the measurements, detailed loading calculations for Bad Homberg and Brussels are being prepared.

The data is also being used to provide an amplitude and phase calibration of the two European superconducting gravimeters located at the two sites and which have not been independently calibrated. A significant phase lag of $0.3^\circ \pm 0.15^\circ$ has already been determined for the superconducting instrument at Bad Homberg from our data.

FUTURE EXPERIMENTS

E.T.15 is presently awaiting formal Indian government approval for importation to Osmania University, Hyderabad in order to commence an experiment there. The equipment is currently under U.K. customs seals. Over the next few years the addition of further strategically placed measurements (ref. 2) should allow many of the present discrepancies between observations, body tide models and ocean tide models to be resolved.

CONCLUSIONS

Considerable progress has been made towards the measurement and interpretation of tidal gravity as a result of work completed during the years of AFOSR support. In summary the main achievements are as follows.

(a) 3 Earth Tide gravimeters have been successfully converted to electrostatic feedback following servicing and re-calibration by the manufacturer. (refs. 1,2,3)

(b) 3 complete sets of support instrumentation have been designed, constructed and tested to ensure reliable, continuous and carefully monitored data to be recorded over periods in excess of six months (refs. 1,2,3)

(c) Considerable knowledge of the behaviour of the gravimeters when controlled by electrostatic feedback has been gained. This led to the definition of operational specifications in terms of instrument response function, linearity, feedback calibration and sensitivity to tilt. (ref. 1)

(d) Calibrations of all 3 gravimeters have been completed on the short range gravity baseline at Hannover F.R.G. This resulted in an amplitude calibration accuracy of $\pm 0.2\%$. The phase response of the instruments at tidal frequencies has been determined to better than $\pm 0.05^\circ$. (refs. 1,3)

(e) The first deployment of the new gravimeter system was at AFGL/Hanscom AFB. In addition to providing the first real test of the system, total tidal corrections can now be made to absolute gravity measurements at the $\pm 1 \mu\text{gal}$ level. This is of sufficient accuracy for present observations. (refs. 2,3)

(f) Tidal experiments at IOS Bidston using all 3 gravimeters have been run. Data from these experiments is being analysed. Preliminary results indicate that there is agreement in amplitude at the $\pm 0.2\%$ level and

that the phases agree within 0.1° . This coherence is of about one order of magnitude better than previous, existing measurements. (this report)

(g) Tidal experiments at Brussels and Bad Homburg have been run. Data from these experiments is undergoing preliminary analysis. It is already clear that the data will make a significant contribution to an understanding of tidal gravity. (this report)

It may be seen that much has already been achieved. With continued support for the 'high precision tidal gravity' programme over the next few years additional data from a number of strategic sites both in Europe and the rest of the world should permit the rigorous testing of the latest body tide and ocean tide models.

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TABLE 1

SUMMARY OF TIDAL GRAVITY DEPLOYMENTS

<u>Instrument</u>	<u>Location</u>	<u>Period of data acquisition</u>	<u>Comments</u>
E.T.10	AFGL Hanscom AFB USA	Sept 1981 to Mar 1982	To provide corrections for absolute gravity
E.T.13	I.O.S. Bidston U.K.	Aug 1982 to Jan 1983	Simultaneous expts. to confirm calibration accuracy and to
E.T.15	I.O.S. Bidston U.K.	Aug 1982 to May 1983	investigate common sources of noise
E.T.15	Bad Homberg F.R.G.	Nov 1983 to Sept 1984	Site of super-conducting gravimeter
E.T.13	Brussels Belgium	Oct 1984 to June 1985 (continuing)	Site of super-conducting gravimeter fundamental tidal gravity station of International Centre for Earth Tides
E.T.10	I.O.S. Bidston U.K.	Mar 1984 to May 1985	
E.T.15	Hyderabad India	-	Awaiting Indian govt. permission: under customs bond

TABLE 2

EXPERIMENTS AT IOS BIDSTON

PRELIMINARY TIDAL RESULTS FOR TIDAL HARMONICS O_1 and M_2

Instrument	Observed gravimetric factors (δ) and phases (K) in degrees			
	M_2		O_1	
	δ	K	δ	K
E.T.13	1.146 ± 0.002	$+0.89^\circ$ $\pm 0.10^\circ$	1.133 ± 0.008	$+0.21^\circ$ $\pm 0.42^\circ$
E.T.15	1.148 ± 0.002	$+0.89^\circ$ $\pm 0.10^\circ$	1.133 ± 0.008	$+0.25^\circ$ $\pm 0.38^\circ$
E.T.10	1.150 ± 0.002	$+0.96^\circ$ $\pm 0.09^\circ$	1.137 ± 0.003	$+0.44^\circ$ $\pm 0.18^\circ$

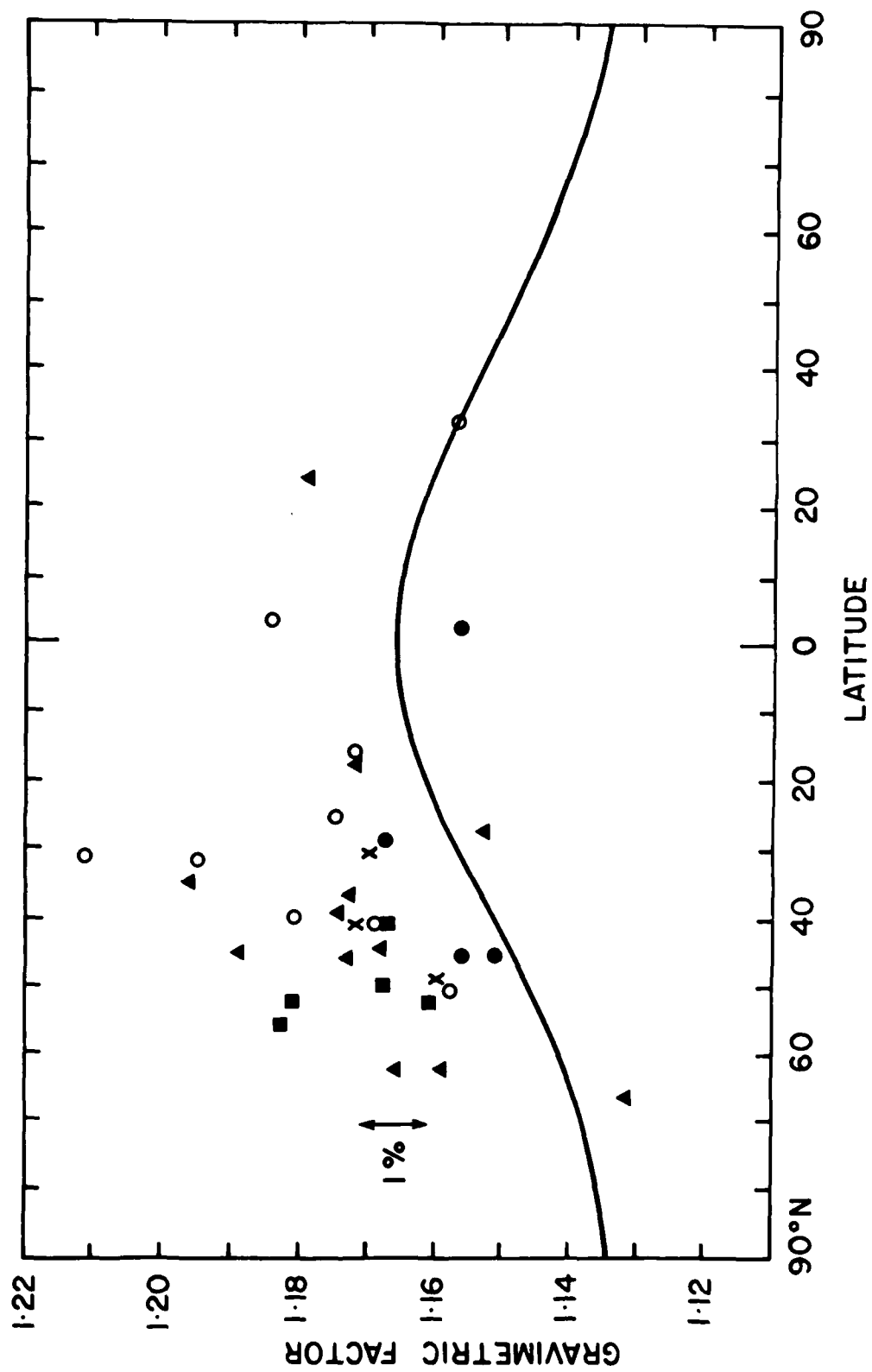
Notes:

1. Phases (K) have been corrected for instrumental phase lags. Negative values of K are phase lags.
2. The corrections due to inertial forces on the observed tidal amplitudes have been applied.
3. Errors are internal 95% confidence limits.
4. No corrections for ocean tide loading have been applied to the data.

FIGURE CAPTIONS

FIGURE 1

The observed M_2 gravimetric factors for stations greater than 300km from the ocean, after correction for tidal loading using the Schwiderski⁵ 1° ocean tide model (after Merriam⁴). The curve is the theoretical M_2 gravimetric factor as a function of latitude as given by the Wahr⁴ body tide model. The different symbols represent different gravimeters. (Note especially both the systematic discrepancy between observation and theory $\sim 1-2\%$ and the scatter of a similar amount).



APPENDIX 1

THE CALIBRATION OF LACOSTE AND ROMBERG TIDAL GRAVIMETERS : INITIAL RESULTS FROM BIDSTON, U.K. BAD HOMBERG F.R.G. AND BRUSSELS, BELGIUM

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JLG-58th meeting March 11-13, 1985

One of the major tasks which presently confronts research into tidal gravimetry is to understand the discrepancy between observations (corrected for tidal loading using the Schwiderski tidal models) and the latest theoretical Earth tide models. This discrepancy may be due in part to the adoption of the standard calibration factor of $\delta = 1.161$ for the O_1 tidal wave at the fundamental station of Brussels.

LaCoste and Romberg Earth Tide meters ET10, ET13 and ET15 have been serviced, converted to electrostatic feedback and calibrated on the short range fundamental gravity baseline at Hannover, FRG. These calibrations indicate that the manufacturer's calibrations may only be trusted at the $\pm 1\%$ level and that with effort a precision $\sim 0.2\%$ may be achieved on the accurate baseline at Hannover. A calibration of this accuracy is sufficient to test the validity of the standard calibration factor. Experiments are still in progress but preliminary results were presented at the meeting which, if substantiated later this year, indicate that a small adjustment to the standard calibration factor (in the right direction) should be applied.

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